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Title: Quantum computing using ultracold neutrons (UCN)

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Quantum computing

using ultracold neutrons (UCN)

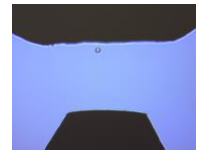
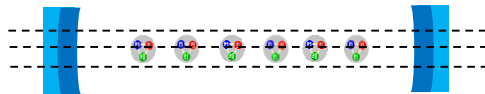
Tongcang Li¹ and Zhehui Wang²

¹*Purdue University*

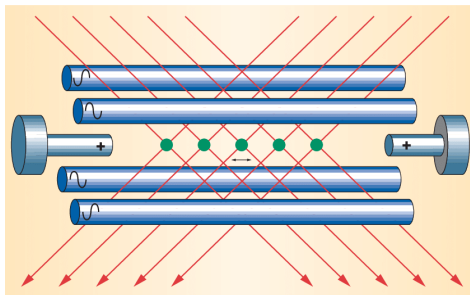
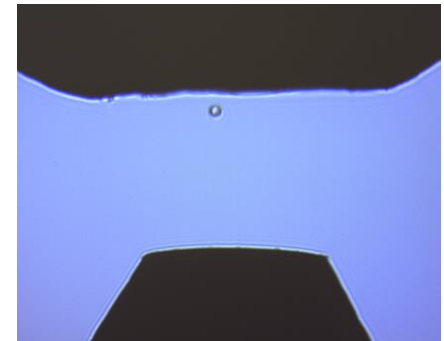
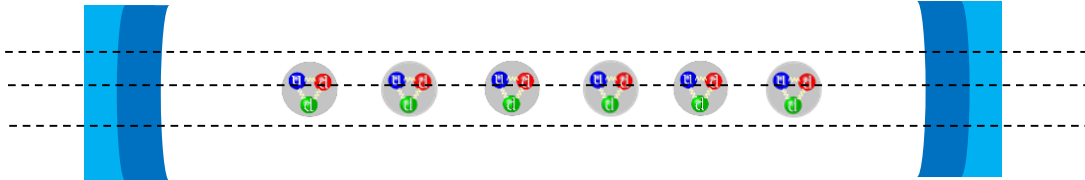
²*Los Alamos National Laboratory*

Oct. 23, 2019

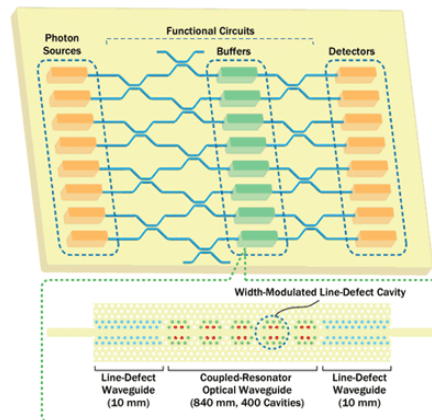
Supported by FY2019, RR on novel computing



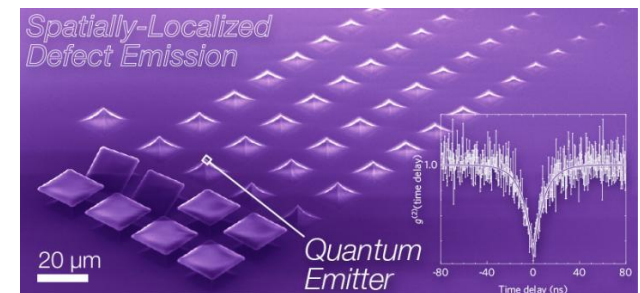
A UCN quantum computer (QC) concept



Steane & Rieffel, Computer (2000)

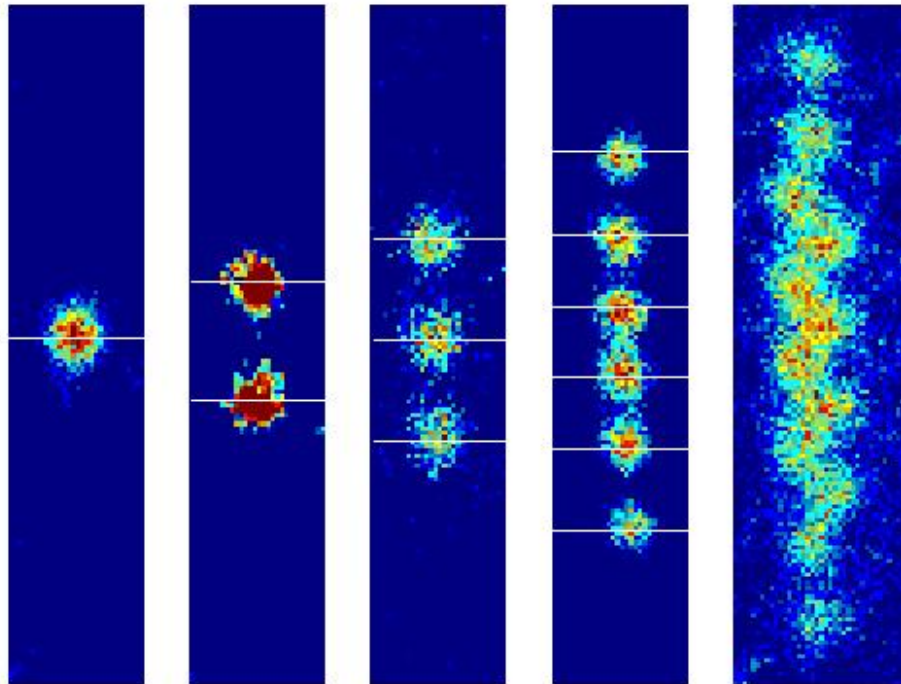


Takesue et al. SR 4 (2014)



Wu et al, APL 114 (2019)

Development path



1, 2, 3, ...

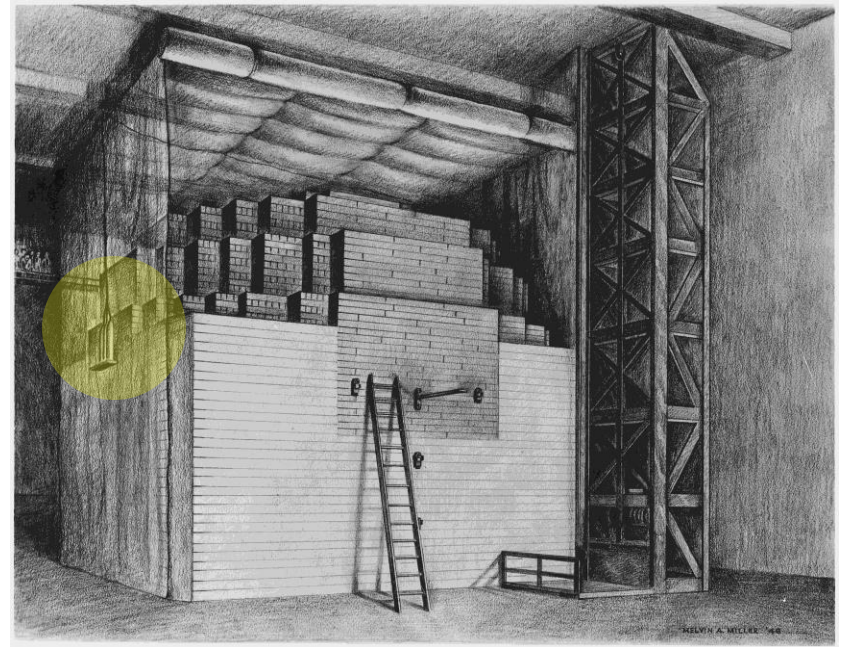
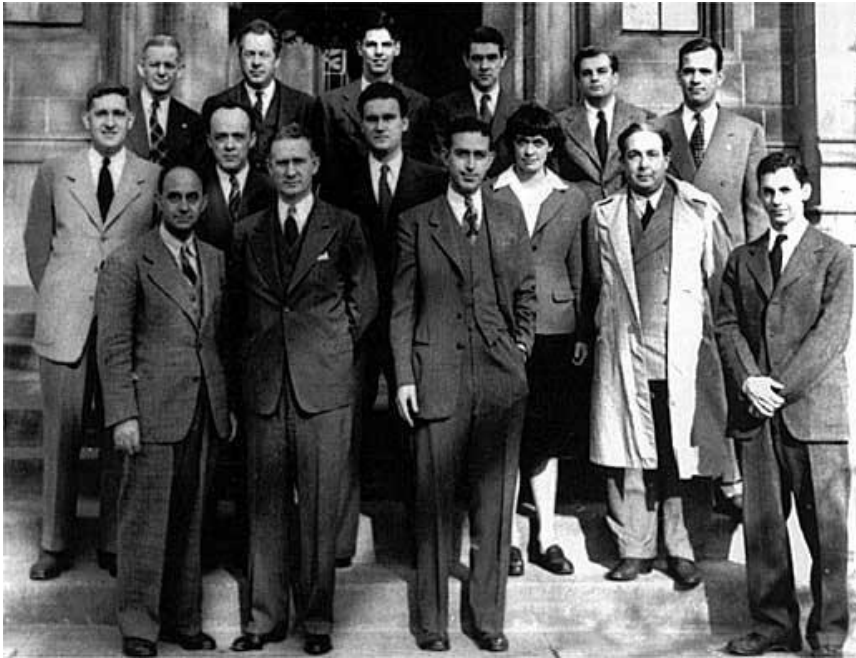
Seidelin et al, PRL 96, 253003 (2006)

Outline

- **Background**
- **DiVincenzo criteria for UCN QC**
- **UCN trapping & entanglement**
- **UCN source & detection**

Fermi & neutron science

On Dec. 2, 1942, Fermi & his team achieved sustained chain reaction, and the first fission reactor. Key elements: fuel, neutron moderator, control rod, neutron detector, and radioactivity detector.



Chicago Pile-1 (CP-1)

Neutron & the standard model of particles

Standard Model of Elementary Particles + Gravity

three generations of matter (fermions)						interactions / force carriers (bosons)		
I			II			III		
mass charge spin	$\approx 2.2 \text{ MeV}/c^2$ $\frac{2}{3}$ $\frac{1}{2}$	$\approx 1.28 \text{ GeV}/c^2$ $\frac{2}{3}$ $\frac{1}{2}$	$\approx 173.1 \text{ GeV}/c^2$ $\frac{2}{3}$ $\frac{1}{2}$	0 0 1	$\approx 124.97 \text{ GeV}/c^2$ 0 0	0 0 2		
QUARKS	u up	c charm	t top	g gluon	H higgs	G graviton		
	d down	s strange	b bottom	γ photon				
	e electron	μ muon	τ tau	Z Z boson				
LEPTONS	$< 2.2 \text{ eV}/c^2$ 0 $\frac{1}{2}$	$< 0.17 \text{ MeV}/c^2$ 0 $\frac{1}{2}$	$< 18.2 \text{ MeV}/c^2$ 0 $\frac{1}{2}$	$\approx 80.39 \text{ GeV}/c^2$ ± 1 $\frac{1}{2}$				
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson				
				GAUGE BOSONS VECTOR BOSONS	SCALAR BOSONS	HYPOTHETICAL TENSOR BOSONS		

A neutron

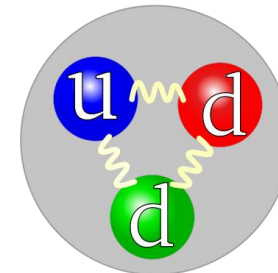
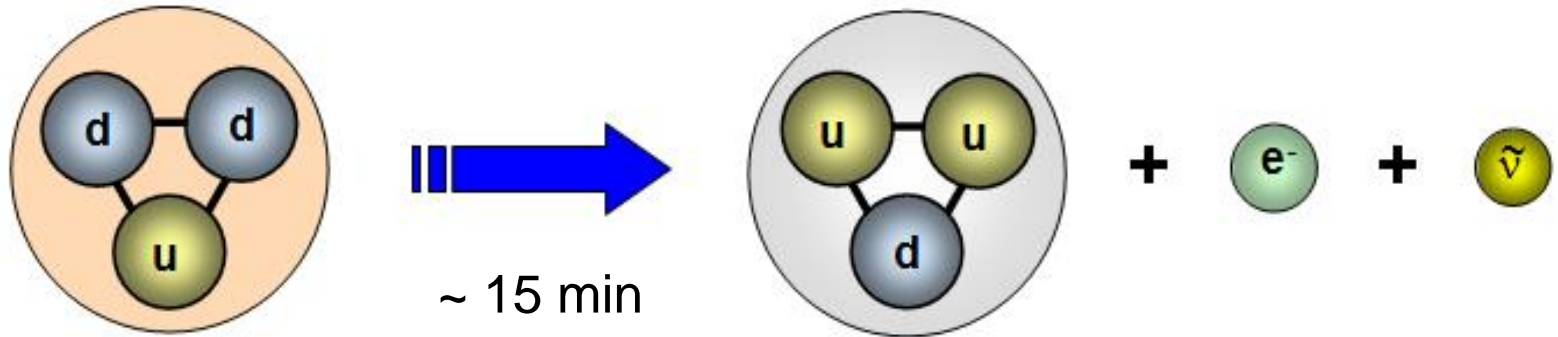


Image credit: Wikipedia/ WWW resources

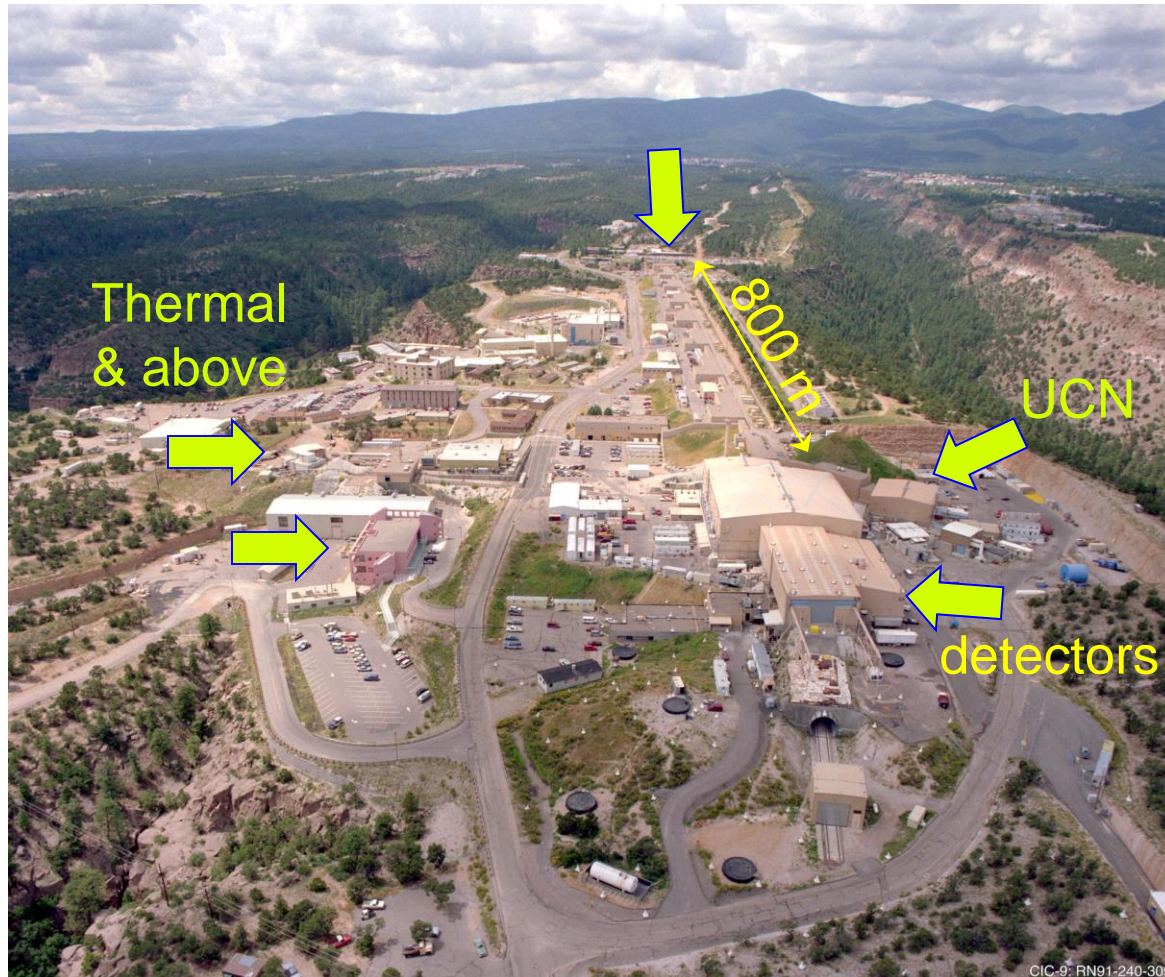
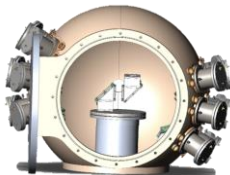
Physics beyond the standard model : Neutron approach

Beta⁻ decay: $n \rightarrow p + \beta^- + \tilde{\nu}$

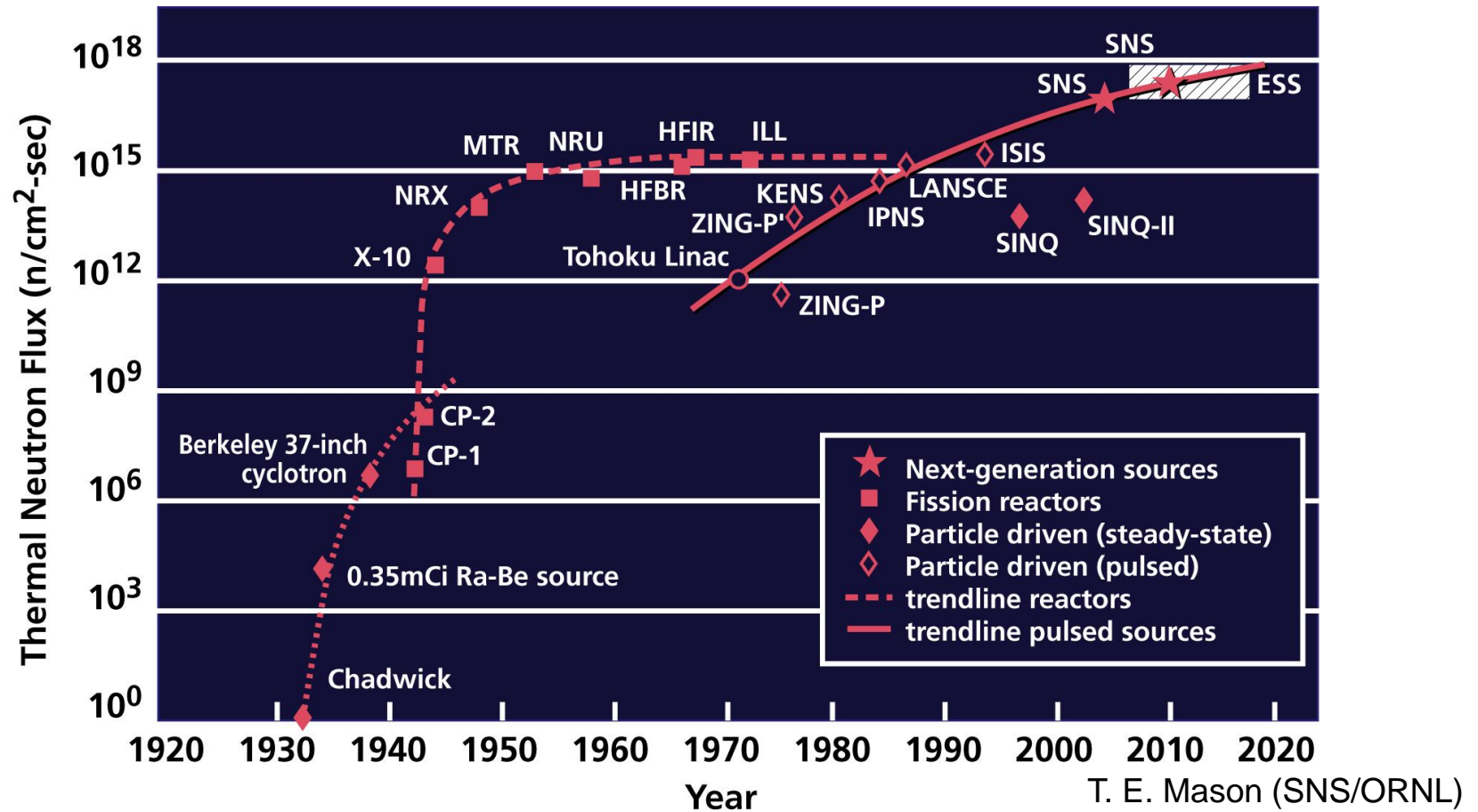


- Neutron β -decay
- Neutron EDM
- Neutron lifetime
- Matter-antimatter
- Dark matter
- ...

Los Alamos Neutron Science Center (LANSCE)



Evolution of neutron source



(Updated from *Neutron Scattering*, K. Skold and D. L. Price: eds., Academic Press, 1986)

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- Background
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- UCN trapping & entanglement
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DiVincenzo criteria for Neutrons

C1: A scalable free neutron system with well characterized qubits;

- the neutron spin or spatially quantized states of neutron ('mini-traps')

C2: The ability to initialize the spin state of neutron qubits;

C3: A coherence time much longer than the operational time;

- Weak neutron interactions demonstrated.

C4: A universal set of quantum gates;

- 'mini-traps'
- Entangled free neutrons and Unitarian transformation

C5: A qubit-specific measurement;

- 'mini-traps'
- QND measurement of a free neutron

C6: The ability to interconvert stationary and flying qubits;

C7: The ability to faithfully transmit flying qubits between specified locations;

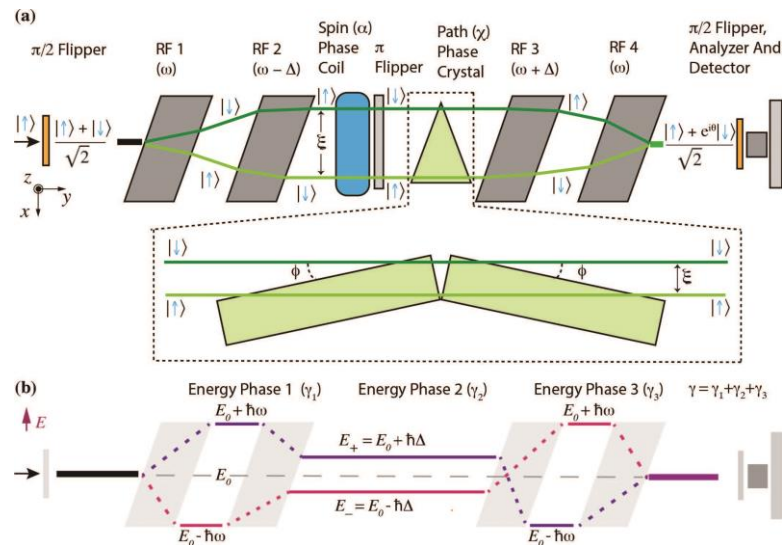
Near-term challenges

Q1: ‘mini-traps’ for free neutrons

Q2: QND measurement of a free neutron;

Q3: Free-neutron entanglement;

“Unveiling contextual realities by microscopically entangling a neutron”



Shen et al, <https://arxiv.org/abs/1908.09823>

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Why ultracold neutrons?

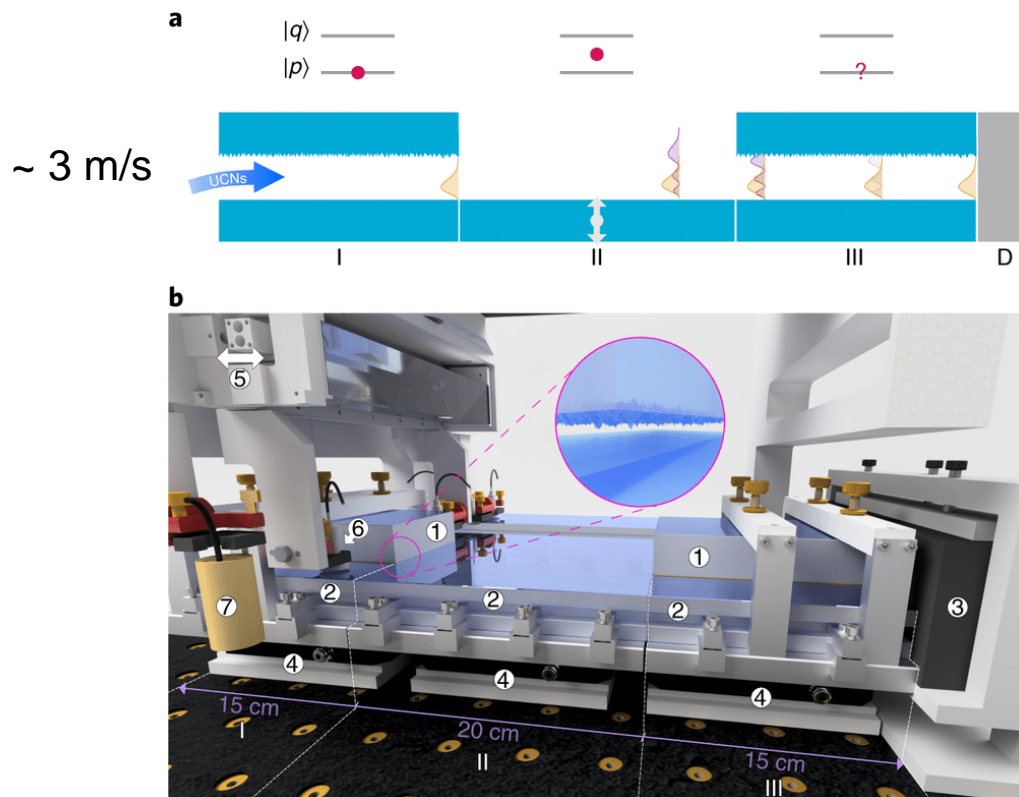
Material:	$V_F^{[8]}$	$v_C^{[9]}$	$\eta (10^{-4})^{[9]}$
Beryllium	252 neV	6.89 m/s	2.0-8.5
BeO	261 neV	6.99 m/s	
Nickel	252 neV	6.84 m/s	5.1
Diamond	304 neV	7.65 m/s	
Graphite	180 neV	5.47 m/s	
Iron	210 neV	6.10 m/s	1.7-28
Copper	168 neV	5.66 m/s	2.1-16
Aluminium	54 neV	3.24 m/s	2.9-10

$^{58}\text{Ni} = 335 \text{ neV}$

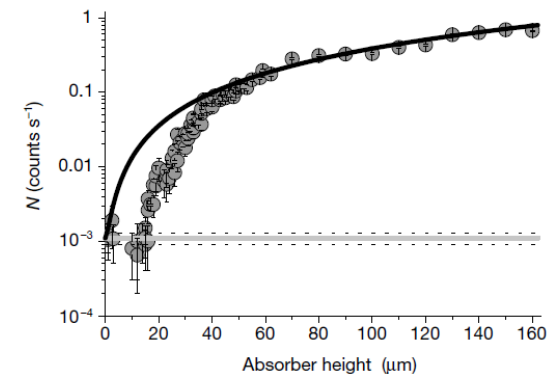
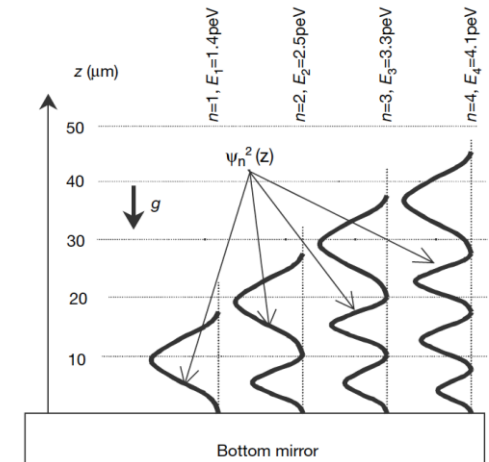
Gravity: 1 m \sim 102 neV
Magnetic field: 1 T \sim 60 neV

Fermi potential

The state of the art

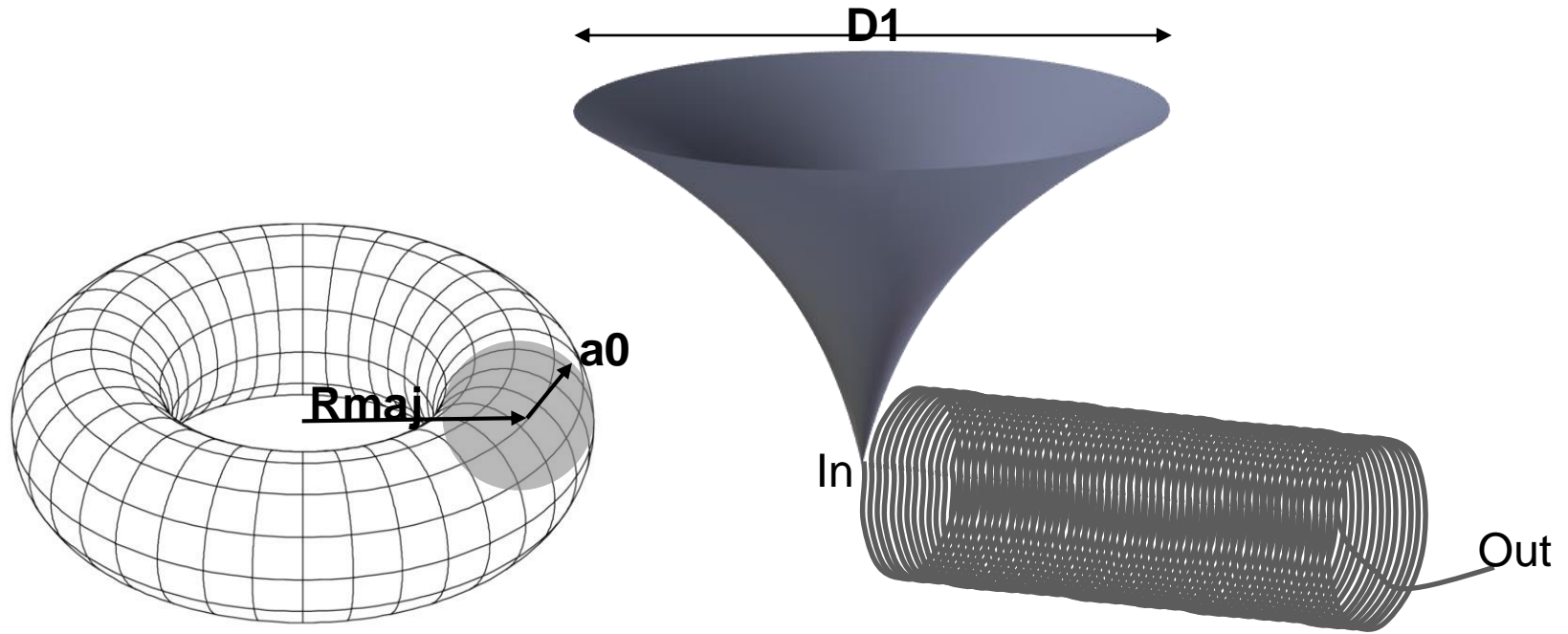


Cronenberg et al, Nature Phys. (2018)



Nesvizhevsky et al, Nature (2002)

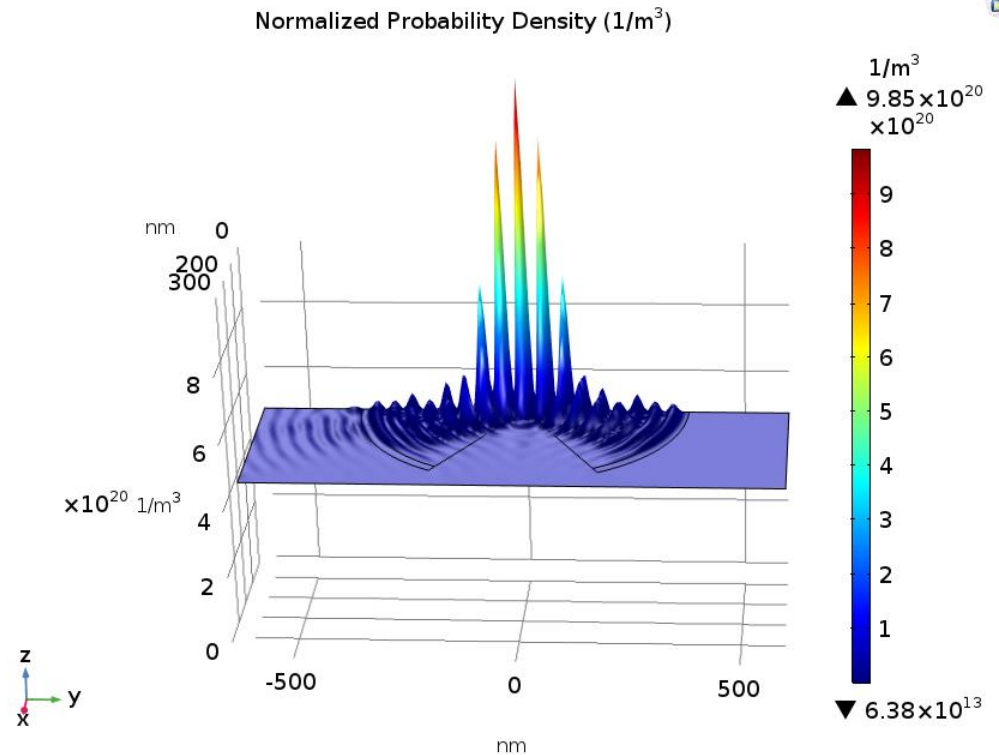
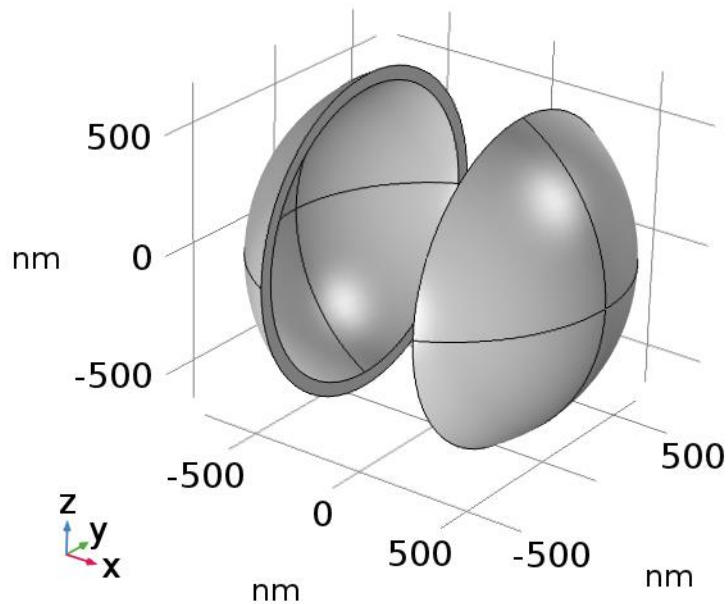
Minitrap concepts



UCN racetrack

UCN fiberguide (~ 1 km long)

Minitrap concepts: nanocavity



Outline

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- UCN trapping & entanglement
- **UCN source & detection**

The LANL UCN Source

C. Morris et al., PRL 89, 272501 (2002)

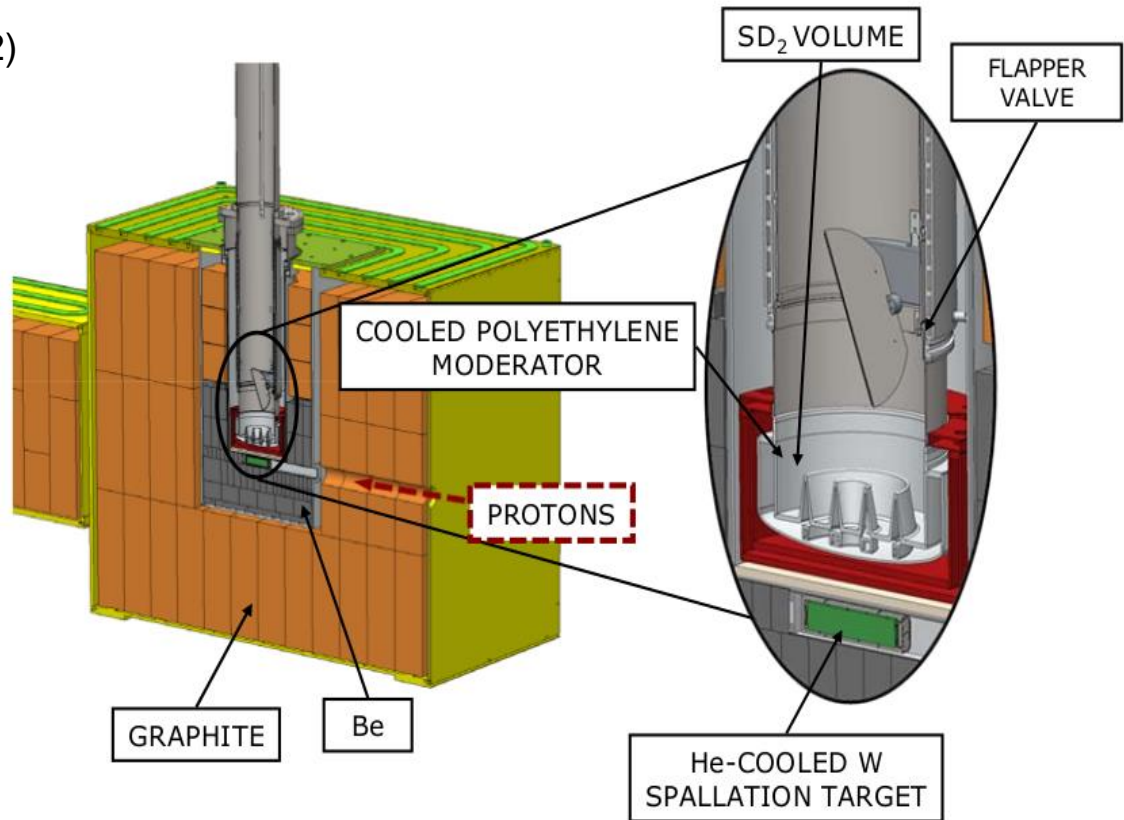
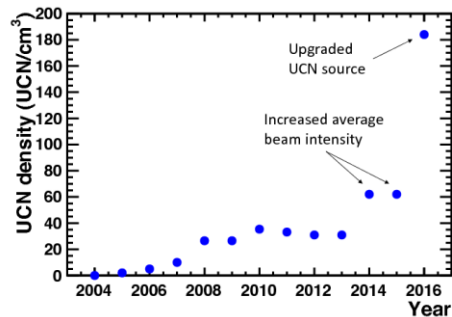
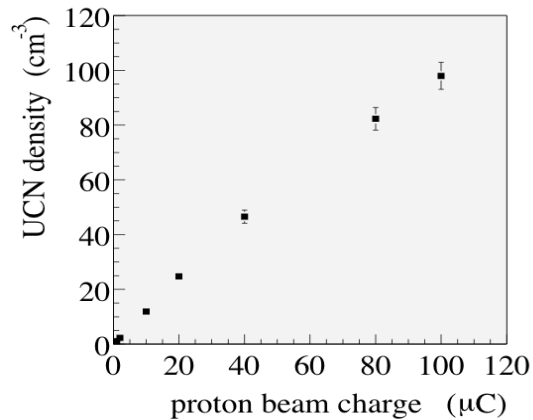


Image credit: UCN collaborations

T. Ito et al., PRC (2018)

UCN science → Physics beyond the Standard Model

- Neutron EDM
- Neutron β -decay
- Neutron lifetime
- Dark matter
- ...

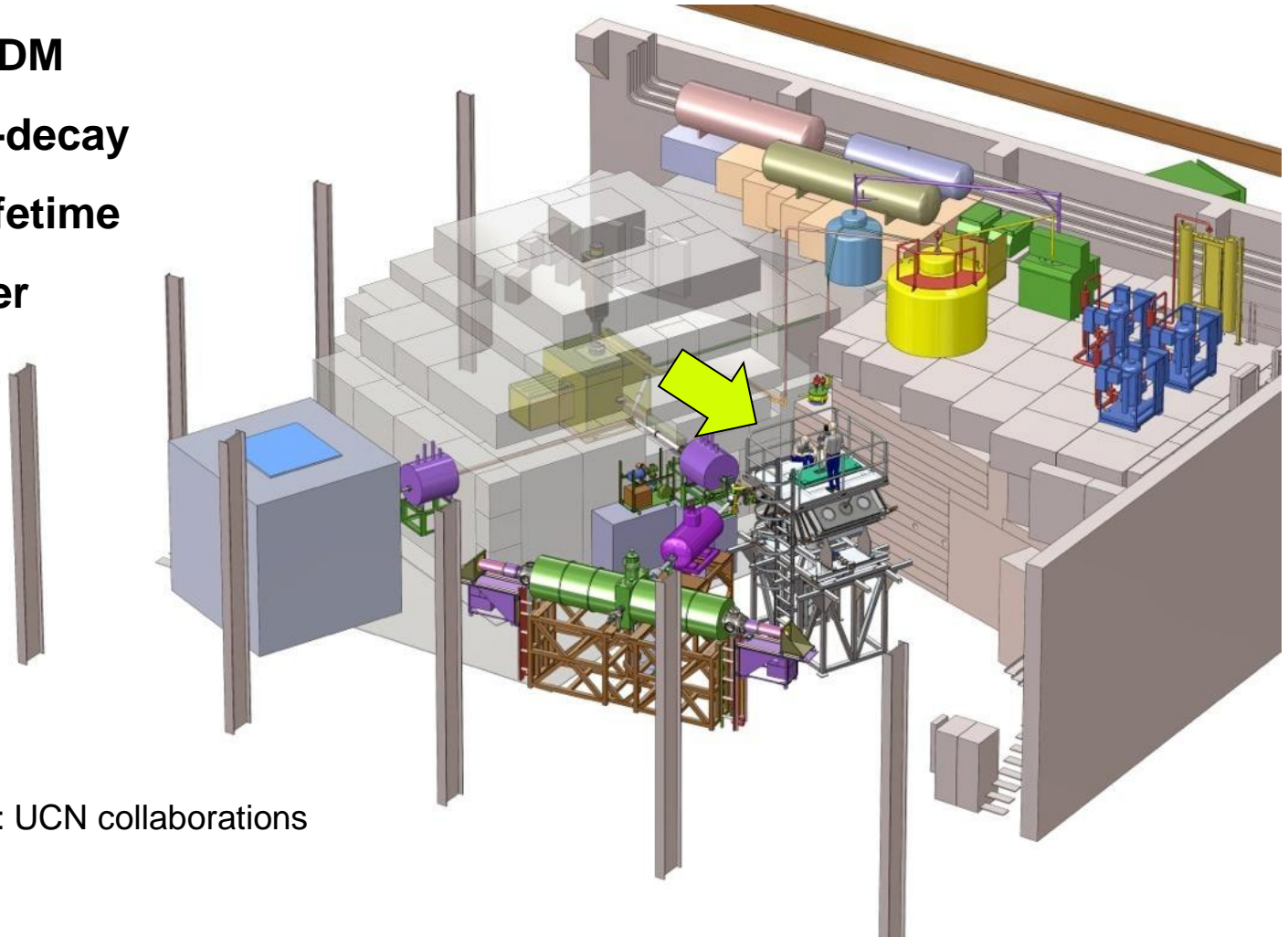
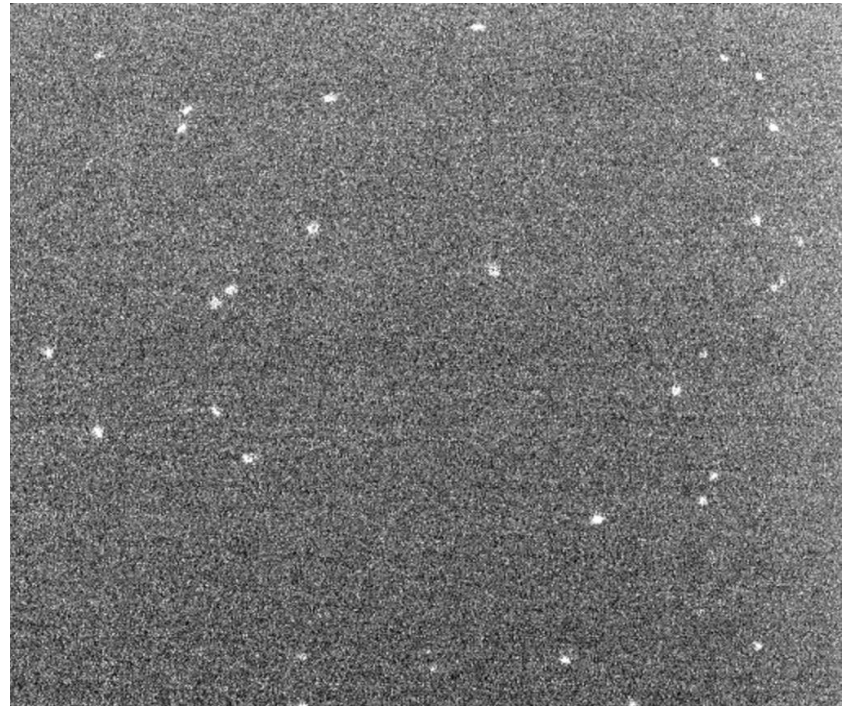
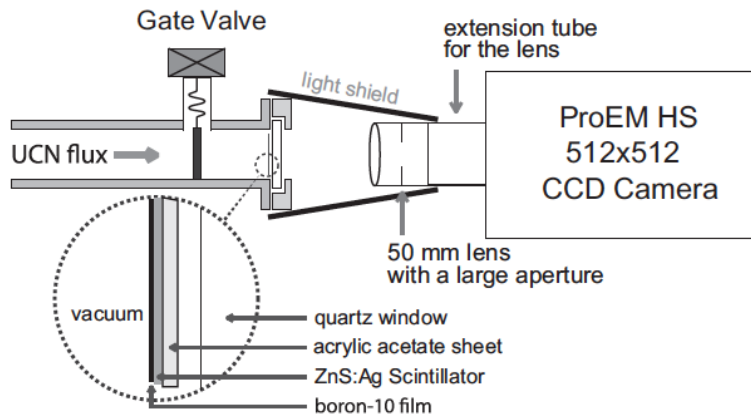


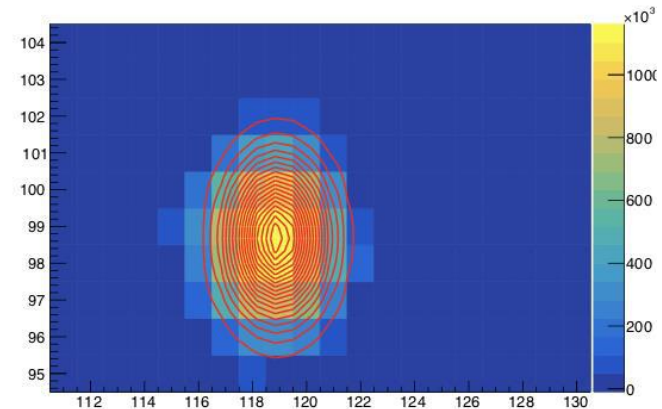
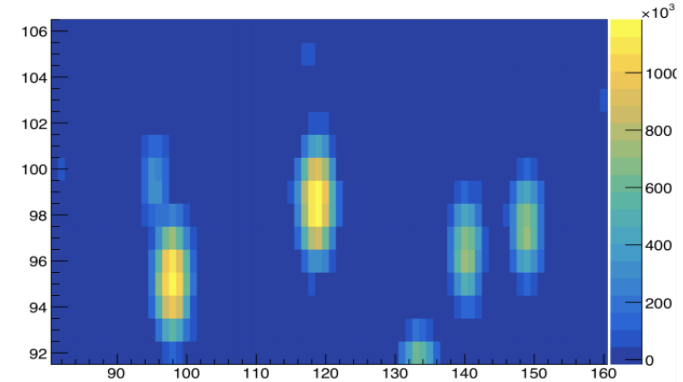
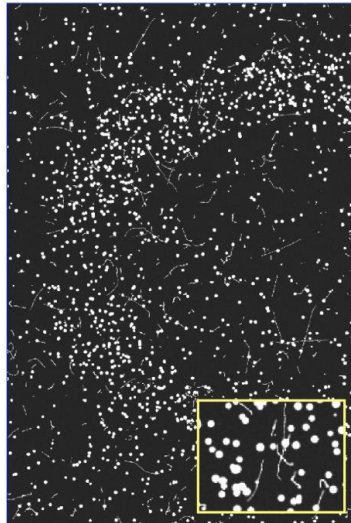
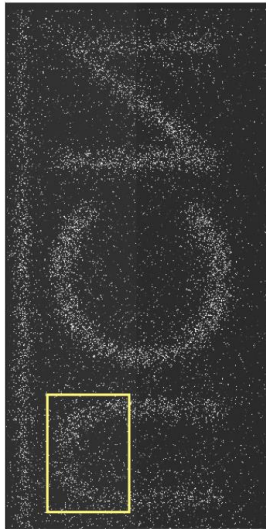
Image credit: UCN collaborations

Seeing individual UCN using CCD cameras



W. Wei et al, NIMA 830 (2016) 36-43.

Improved resolution meeting quantum state needs



K. Kuk et al, <https://arxiv.org/abs/1903.01335> (2019).

QND of single photons

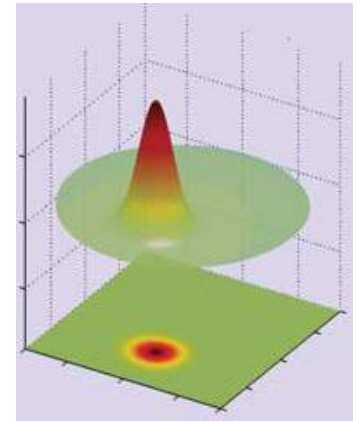
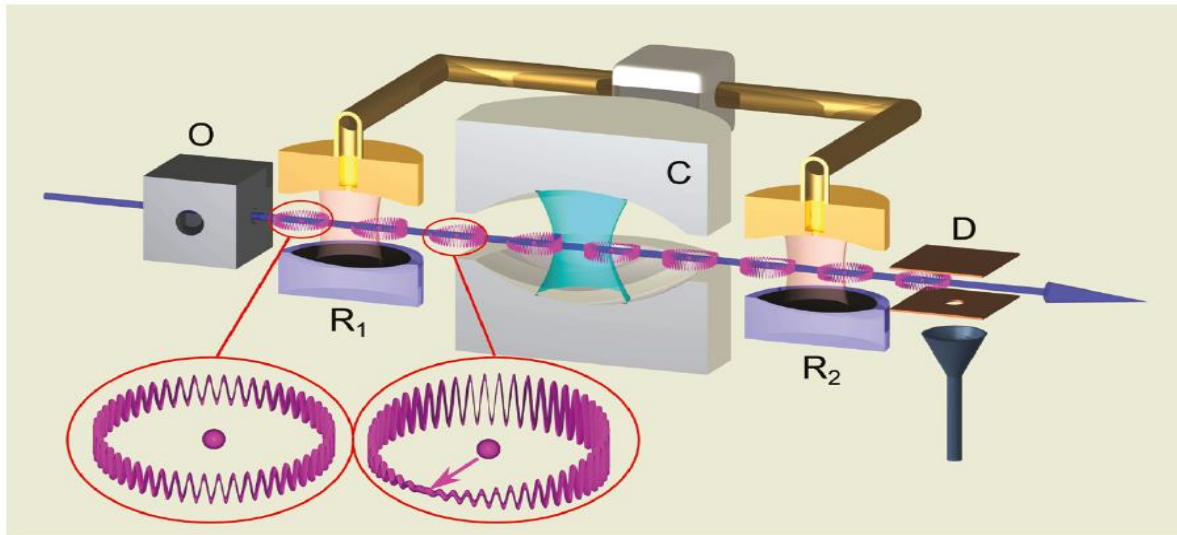
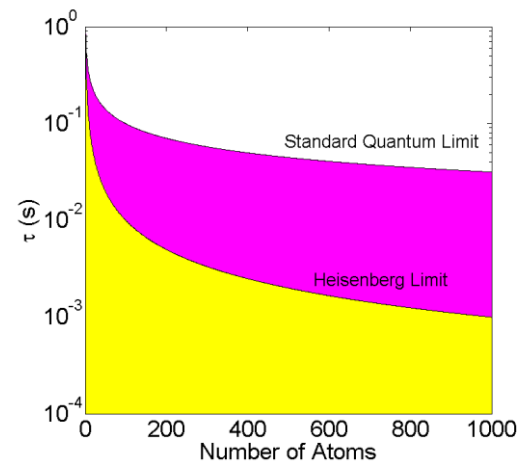
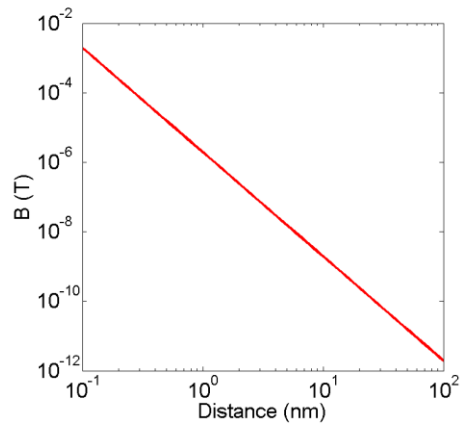
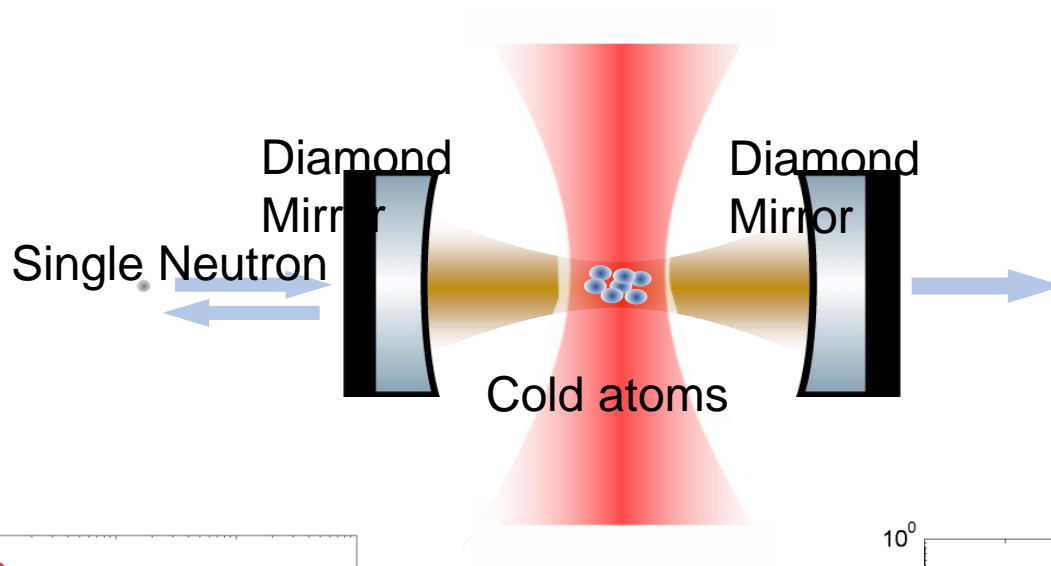


FIGURE 10. The Cavity QED Ramsey interferometer set-up. The insets show sketches of the circular atom in an energy eigenstate (left) and in a superposition state after interaction with the microwave pulse in R_1 (right). (Reprinted with permission from [49], © American Physical Society).

QND of a free neutron difficult yet feasible



Summary

- A UCN quantum computer(QC) is theoretically allowed
- Technology development can be broken down into multiple key components
- LANSCE and other assets at LANL provide solid foundation for UCN QC demonstration

The UCN τ Collaboration

Indiana University/CEEM

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B. A. Slaughter, W. M. Snow, J. Vanderwerp

Joint Institute for Nuclear Research

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D. Barlow, L. J. Broussard, S. M. Clayton, M. A. Hoffbauer, M. Makela, J. Medina, D. J. Morley, C. L. Morris,
R. W. Pattie, J. Ramsey, A. Saunders, S. J. Seestrom, S. K. L. Sjue, P. L. Walstrom,
Z. Wang, T. L. Womack, A. R. Young, B. A. Zeck

North Carolina State University

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